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Faulting of Gas-Hydrate-Bearing Marine Sediments — Contribution to Permeability

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Abstract

Extensive faulting is observed in sediments containing high concentrations of methane hydrate off the southeastern coast of the United States. Faults that break the sea floor show evidence of both extension and shortening; mud diapirs are also present. The zone of recent faulting apparently extends from the ocean floor down to the base of gas-hydrate stability. We infer that the faulting resulted from excess pore pressure in gas trapped beneath the gas hydrate-bearing layer and/or weakening and mobilization of sediments in the region just below the gas-hydrate stability zone. In addition to the zone of surface faults, we identified two buried zones of faulting, that may have similar origins. Subsurface faulted zones appear to act as gas traps.

Introduction

Methane hydrate in continental margin settings, especially in passive margins, commonly occurs in hemipelagic clay/silts. These deposits appear to have some of the highest concentrations of hydrate, but they also have low permeability, presenting an impediment to extraction of hydrate-derived gas. Recently, seismic profiling by the U.S. Geological Survey and drilling by the Ocean Drilling Program (ODP) have been carried out on the Blake Ridge off the coast of the southeastern United States, a location having high gas-hydrate concentrations. Extensive faulting is noted in these deposits, probably partly associated with gas-hydrate processes. The faulting may create zones of high permeability that could act as reservoirs for exploitation, or that might contain shallow gas deposits that could represent drilling hazards.

Methods

Most of the profiles shown in this paper were collected with seismic systems designed to image the gas-hydrate zone and the region directly below it (1.5-2.0 s below the sea floor). They are part of a set of 4-km-spaced seismic profile that cover a 4,800 square-kilometer area on the crest of the Blake Ridge. Moderately small, pneumatic seismic-sound sources provided adequate power to penetrate below the region of gas-hydrate stability, while still maintaining the best possible resolution. Sources used were a 160-cubic inch (2.62-liter) airgun or a generator/injector (GI) gun, in which the generator chamber (which generates the primary signal) was 105 cubic inches (1.72 liters), and the injector chamber (which controls bubble pulsing) was also 105 cubic inches. Swept-frequency ("chirp", 2 to 7 kHz) subbottom-reflection data were obtained from a deep-towed, multisensor system; they provide data on near-surface sediments (upper 60 m).

Blake Ridge

The Blake Ridge (Fig. 1) is a broad, generally smooth sedimentary accretionary ridge — a deep-sea sediment drift deposit — that is accreting at the site of interaction of major ocean currents^{1,2,3,4}. Deposition on its southern flank and erosion on its northern flank have resulted in slow southward migration of the feature. The ridge is considered to be the area where gas hydrate may be most concentrated on the United States Atlantic margin⁵. The surface of the ridge is generally smooth except for minor differential erosion features on its northern (eroding) flank⁶, but, at the crest of the ridge at about 31° 50'N to 32°N, a complex topographic depression covers an area of about 33 by 22 km (Fig. 2)

Faults

Shallow Faults. Seismic-reflection profiles clearly show that the complex topographic depression is a faulted structural collapse (Fig. 3). Faulting took place in a surface layer of sediment about 0.5 to 0.6 s thick (about 400 to 500 m). Seismic profiles indicate that these faults consistently extend from the sea floor to near the base of the gas-hydrate stability zone. The base of the gas-hydrate stability zone is assumed to be identified by the Bottom Simulating Reflection (BSR, note

Fig. 3), which is considered to mark the acoustic contrast between hydrate-bearing sediments above and free-gas-bearing sediments below⁷.

The structure displayed in Fig. 3 includes normal faults with throws of as much as 150 m, which bound downdropped and rotated blocks. Seemingly, this structure might have formed by extension of the surface layer by about 12 percent across the collapse feature, but it is clear from the regional structure that the ridge has not been deformed by any such overall extension. Our regional seismic survey shows that there has been no outward movement of the ridge flanks and that no landsliding has taken place. On some profiles, the results of compressive movement are apparent; the fault blocks have been forced up, and the blocks have been internally deformed and shortened. Sediment diapirs that arise from the depth of the base of gas-hydrate stability (as defined by the BSR) also are present.

Most of the faults are oriented parallel to the ridge crest (NW), but at the western end of the collapse feature, the faults change to a N-S orientation. A deep-towed, very high-resolution, chirp (swept-frequency) profile crossing these faults (Fig. 4) shows the tilted fault blocks with strata dipping toward the west (left). Much of the profile shows a thin drape of post-faulting sediment covering the sea floor, but in the depressions at the feet of the fault scarps this drape is absent. This suggests that fluids, including gas, may still be venting from the faults. Escape of gas from beneath the sea floor, where it would be stable in the hydrate phase, has been demonstrated in the Blake Ridge area⁸.

Deeper Faults. The collapse at the crest of the Blake Ridge is not unique, only the most recent example of such faulting. Deeper comparable fault sets may be more significant with regard to trapping of gas.

One set of deeper faults occurs further seaward along the Blake Ridge on profile 2B (location Fig. 2; profile Fig. 5). This is marked by disruptions at depths of about 4.4 to 4.9 s between shotpoints 400 and 900. This faulted zone may not yet be completely sealed to form a gas trap. Rather, it may still be leaking as suggested by the lack of a BSR or comparable strong reflections near the top of the faulted region, which would signify the presence of gas. Faults associated with a slightly dropped graben (shotpoints 500 to 600, Fig. 5) may represent escape pathways for gas.

A second set of deeper faults is much more extensive on the southwestern flank of the ridge and actually seems to form a gas trap. Line 92-11 is a profile from this locality (Fig. 6; location of profile shown on Figs. 1 and 2). Vertical extent of the faults appears to be about 0.5-0.6 s (from about 4.4 to 5.0 s at the southwest end of line 92-11). This represents a vertical extent about the same as that of the present gas-hydrate stability zone in the area, just as with the surface set of faults. The faulting extends laterally across much of the ridge, and the top of the faulted zone approximately follows a depositional horizon in our interpretation. The top of the zone of faulting occurs above the base of gas-hydrate stability (BSR) on the southwest flank of the ridge, whereas it dips below the BSR near the ridge crest. The region of intersection (approximately shotpoints 6950 to 1700) is shown in Fig. 7. In both figures (Figs. 6

and 7) the top of the faulted zone is marked with squares and the BSR is marked with circles.

Indications of free gas exist at the top of the faulted zone both beneath the BSR at ODP site 994, and above the BSR to the southwest on the ridge flank (Figs. 6 and 7). Vertical seismic profiles at the ODP 994 well indicate velocities of about 1750 - 1800 m/s through the lower part of the hydrate zone and such velocities continue downward beneath the hydrate zone to the strong reflections at the top of the interpreted faulted zone⁹. Below the reflection, velocities drop to about 1500 m/s, strongly suggesting presence of free gas. Further southwest, where the top of the faulted zone rises into the gas-hydrate stable zone, the reflection shows apparent phase reversals compared to the sea floor, indicating an acoustic impedance inversion, which again is most easily explained by low velocity produced by free gas. Therefore, as a preliminary interpretation, we suggest that the strong reflection at the top of the faulted zone may represent a gas trap extending across much of the Blake Ridge.

Growth Faults. The faults considered so far seem to exist in layers that are about the thickness of the gas-hydrate stability zone. In contrast, other faults appear to extend over greater vertical distances and, as they seem to be growth faults (having decreasing throw upward), seem to have been more or less continuously active for a long period (Fig. 8). These faults probably just result from compaction of the sedimentary deposits of the Blake Ridge.

Summary and Conclusions

Faulting is common in an area of extensive gas-hydrate development off the coast of the southeastern United States. The most recent (shallowest) faults show significant extensional and compressional effects and evidence of mud diapirism all restricted to the depth range of gas-hydrate stability, which extends from the sea floor down to the bottom simulating reflection (BSR). The BSR marks gas that has accumulated at the base of the hydrate stable zone. At least one older episode of faulting seems to be restricted to an equivalent (400-500 m) thickness of sediments. We infer that the faulting and collapse of near-surface strata within the zone of gas-hydrate stability is caused by generation of overpressures beneath the gas-hydrate stable zone and/or by formation of a weakened, mobilized layer just beneath the gas-hydrate stable zone due to presence of trapped high concentrations of fluids. A specific sedimentary interval of hydrate stability will persist only for a short time before the sea floor of the Blake Ridge accretes and the entire gas-hydrate stability zone moves upward as the isotherm that controls its base moves upward. Therefore we conclude that the faulting in these fairly thin (~500 m) intervals occurred in a geologically brief time interval. Growth faults that extend through thicker zones were active for longer times.

At some places, gas seems to be trapped by permeability variations associated with faulting both below and within the zone of gas-hydrate stability, whereas, at other sites, gas seems to be escaping at the sea floor. Both phenomena require that free gas exist within the zone of gas-hydrate stability, but at the temperature/pressure conditions anticipated in the gas-hydrate stability zone, gas bubbles in the presence of water

would form hydrate. For gas to enter the zone from below, or exist in it, or pass through it to escape at the sea floor, the gas must find channelways where no water is present (perhaps locally sealed off by gas hydrate) or where the temperature is sufficiently warm to prevent hydrate formation (perhaps due to passage of warm fluids from greater depth). Chemical changes and thermodynamic phenomena can also affect the stability of hydrate, but it is difficult to imagine one that would allow gas to exist well within the stability zone for gas hydrate on the Blake Ridge (away from salt diapirs). The zones of higher permeability associated with faults may provide sites where gas might be produced and, by pressure reduction, gas from adjacent hydrate might be accessed.

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References

1. Markl, R. G., and Bryan, G. M. "Stratigraphic evolution of Blake Outer Ridge." *American Association of Petroleum Geologists Bulletin*, (1983) 67, 666.
2. Tucholke, B. E., and Mountain, G. S., "Tertiary paleoceanography of the western North Atlantic Ocean." Vogt, P. R. and Tucholke, B. E. (eds) *The Geology of North America.. The Western North Atlantic Region*: Geological Society of America, Boulder CO, (1986) M 631.
3. McCave, I. N., and Tucholke, B. E., "Deep current-controlled sedimentation in the western North Atlantic." Vogt, P. R. and Tucholke, B. E. (eds.), *The Geology of North America.. The Western North Atlantic Region.. Geological Society of America*. Boulder CO, (1986) M 451.
4. Dillon, W.P., and Popenoe, Peter. *The Blake Plateau and Carolina Trough*, in Sheridan R.E. and Grow, J.A., (eds.). *The Geology of North America. The Atlantic Continental Margin*. U.S., Geological Society of America, Boulder CO, (1988) 1-2, p. 291-328.
5. Dillon, W. P., Lee, M. W., and Coleman, D. F., "Identification of marine hydrates in situ and their distribution off the Atlantic coast of the United States" Sloan, E.D., Jr., Happel, John, and Hnatow, M.A. (eds.) *International Conference on Natural Gas Hydrates. Annals of the New York Academy of Sciences*, (1994) 715, 364.
6. EEZ-Scan 87 Scientific Staff, "Atlas of the U.S. Exclusive Economic Zone, Atlantic continental margin," U. S. Geological Survey, *Miscellaneous Investigations Series I-2054*, (1991) 174 p.
7. Dillon, W. P., and Paull, C. K., "Marine gas hydrates - II: Geophysical Evidence" *Natural gas hydrates--properties, occurrences and recovery*, Cox, J. L. (ed.) Butterworth Publishers, Boston, Mass. (1983) 73.
8. Paull, C.K., Ussler, William, III, and Borowski, W.S.: "Methane-rich plumes on the Carolina continental rise--Associations with gas hydrates," *Geology*, (1995) 23, 89.
9. Holbrook, W.S., Hoskins, Hartley, Wood, W.T., Stephen, R.A., Lizarralde, Daniel, and Leg 164 Scientific Party: "Methane hydrate and free gas on the Blake Ridge from vertical seismic profiling" *Science* (1996) 273, 1840.

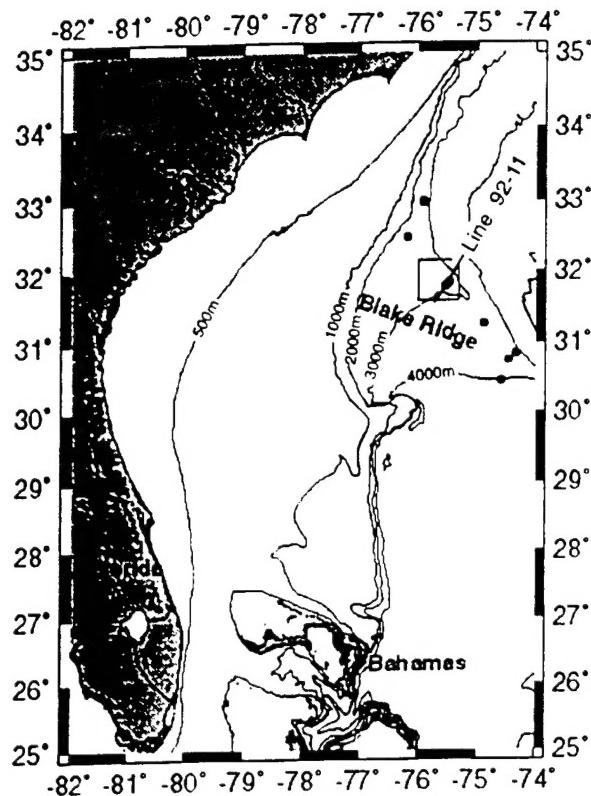


Fig. 1—Location of survey area on the Blake Ridge off the southeastern United States. Dots indicate Ocean Drilling Program and Deep Sea Drilling Project drillsite. Square indicates location of Fig. 2.

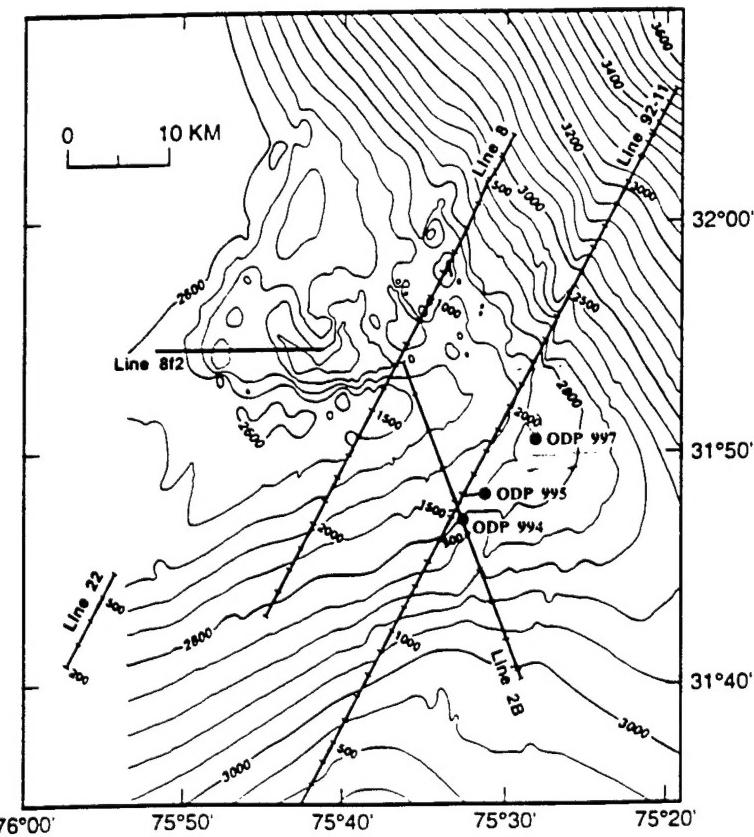


Fig. 2—Detailed bathymetry of the central part of the study area. Map was generated from available echo-sounder profiles. Locations are indicated for seismic profiles shown in this paper. Region of rough topography at the crest of the ridge from approximately 31°50'N to 32°N was formed by extensive faulting.

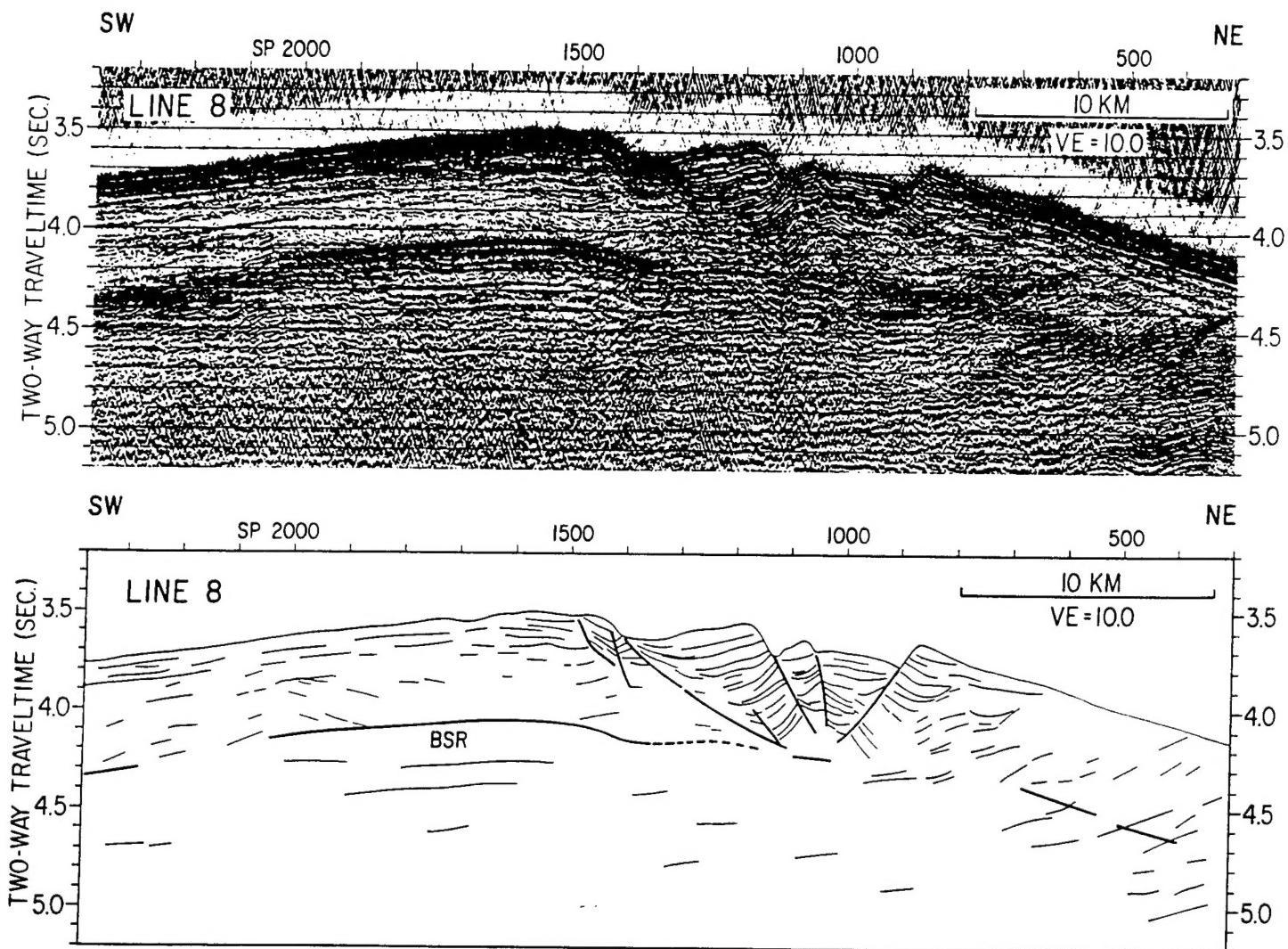


Fig. 3—Airgun seismic line 8 across the crest of the Blake Ridge showing structure of the collapse depression between shotpoints 1500 and 900. Location in Fig. 2.

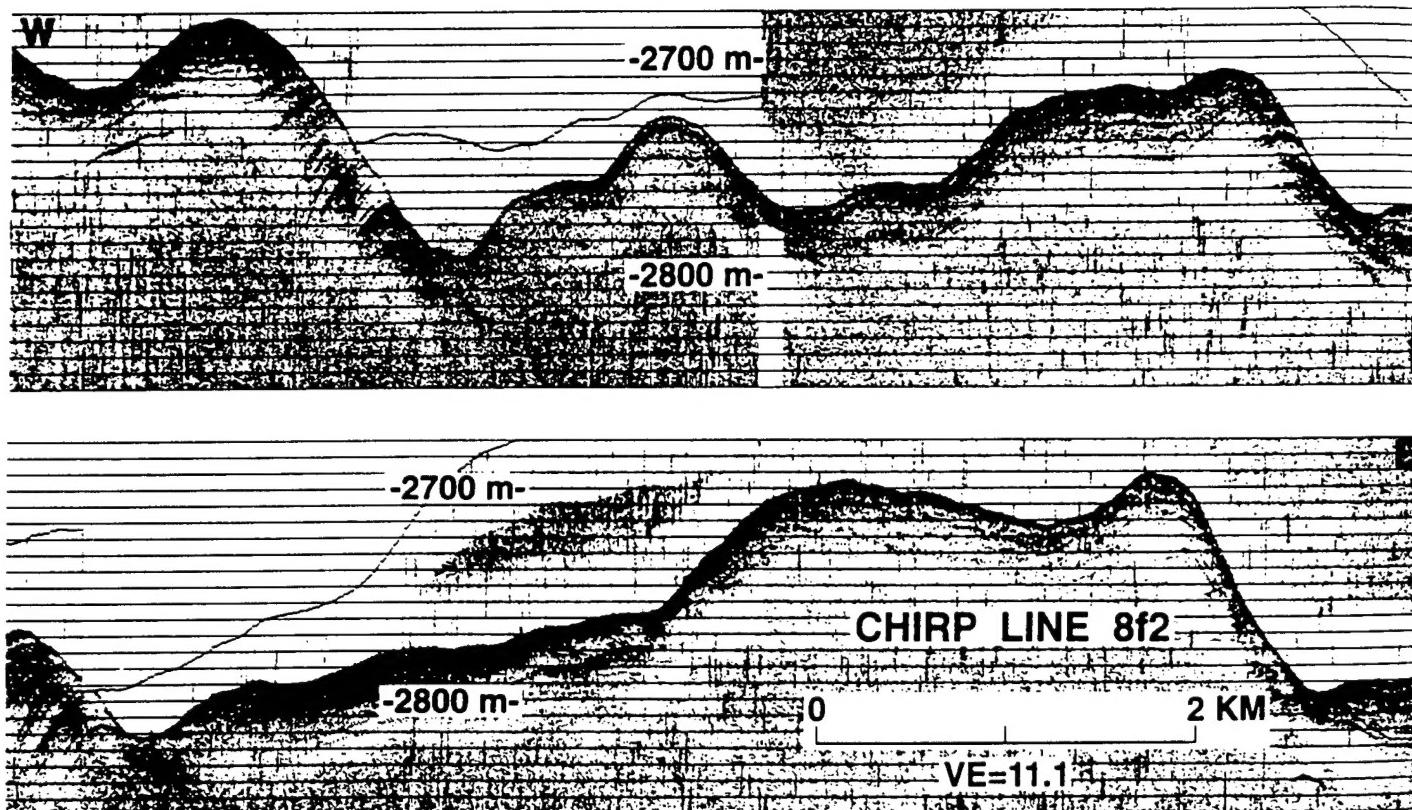


Fig. 4—High-resolution, chirp (swept frequency) profile showing fault scarps with inferred vents at their bases. Location shown in Fig. 2

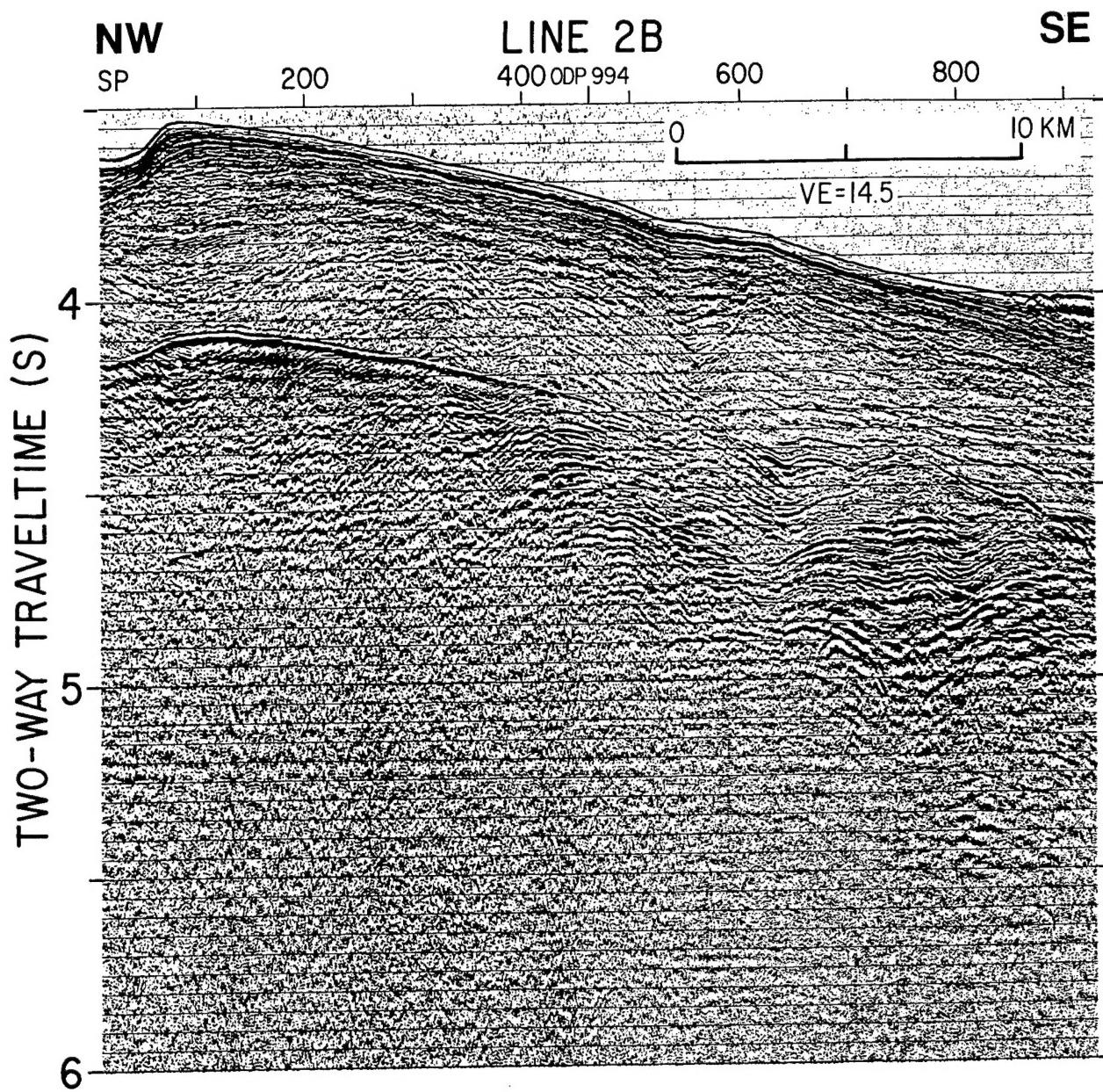


Fig. 5—Generator-injector gun seismic line 2B showing buried faults at depth of about 4.4-4.9 s between shotpoints 400-900. The weak BSR in this area compared to the much stronger BSR to the left (at about 0.5 s below the sea floor) indicates that there is much less gas trapped beneath the hydrate zone; the gas may have escaped up faults between ~ shotpoints 500 and 600.

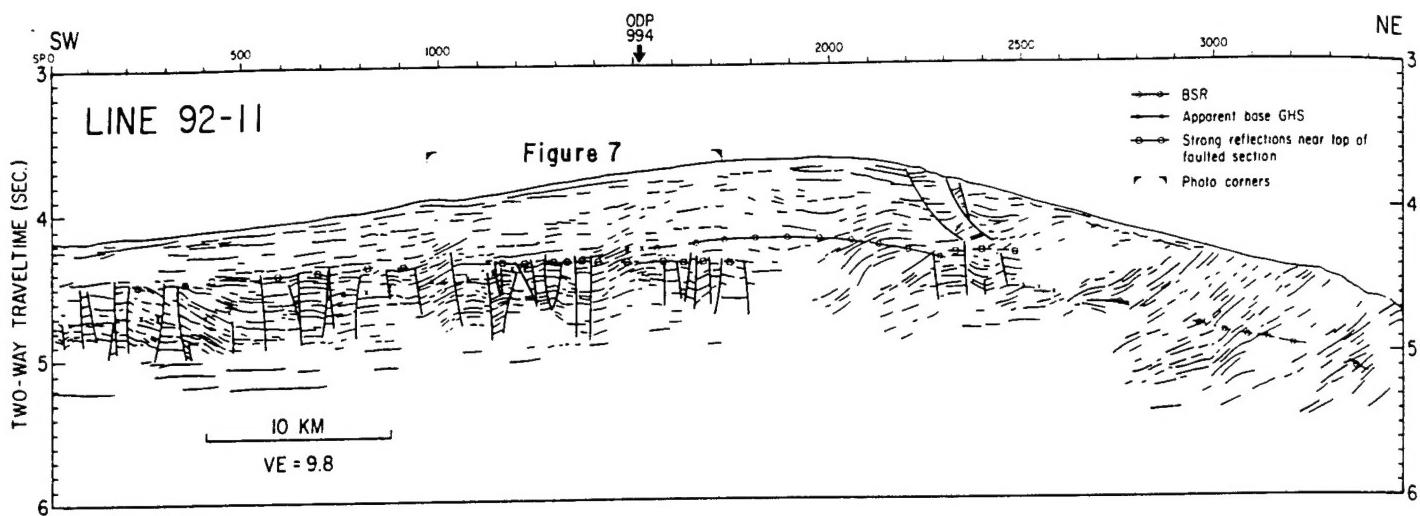


Fig.6—Line drawing interpretation of airgun seismic line 92-11. Note that the strong reflection near the top of the faulted section (marked with squares) extends from below the base of gas hydrate stability/BSR (marked with circles) to above it on moving from the crest of the Blake Ridge to the southwestern flank.

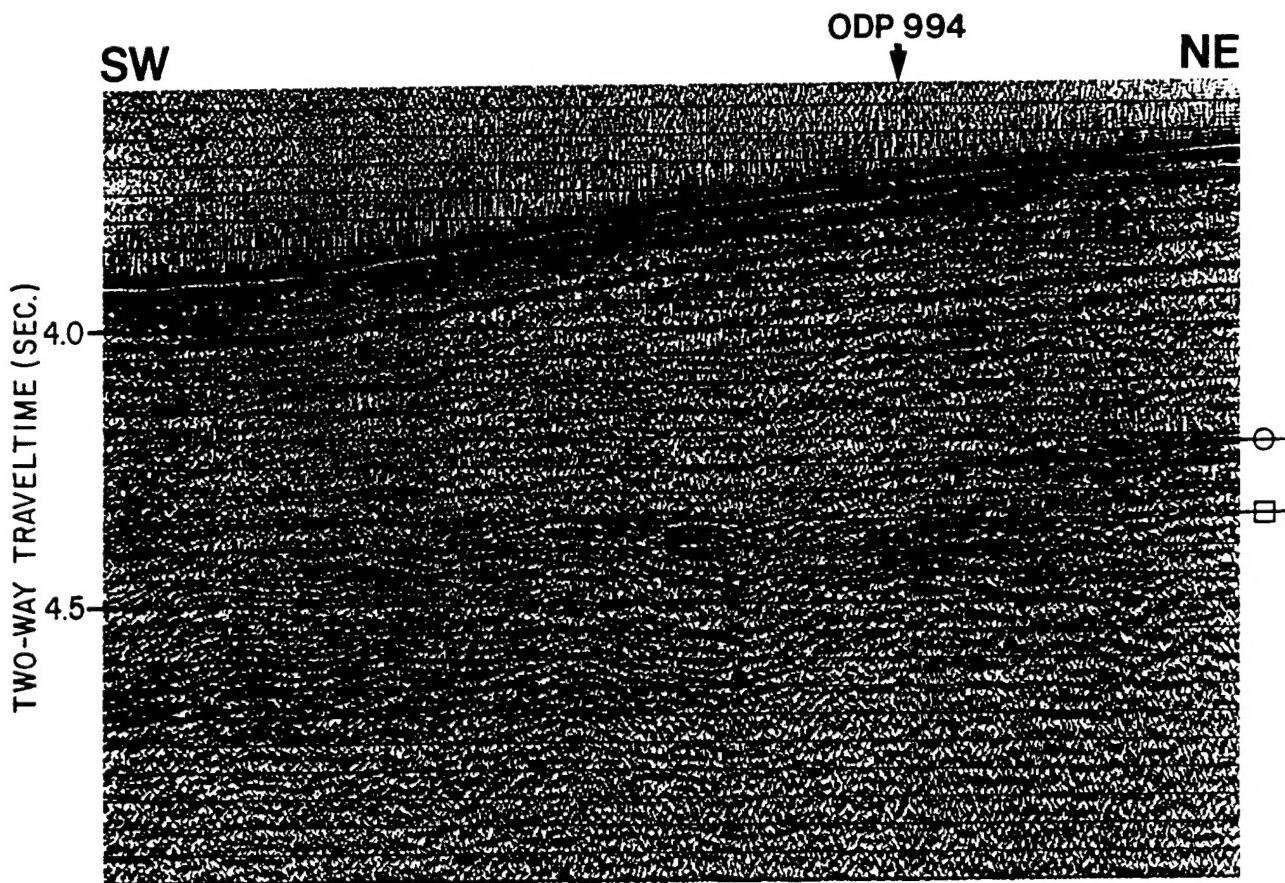


Fig.7—Part of seismic line 92-11. Location of this photograph is shown by brackets in Fig. 6. Circle marks BSR and square marks strong reflection near top of faulted section as in Fig. 6.

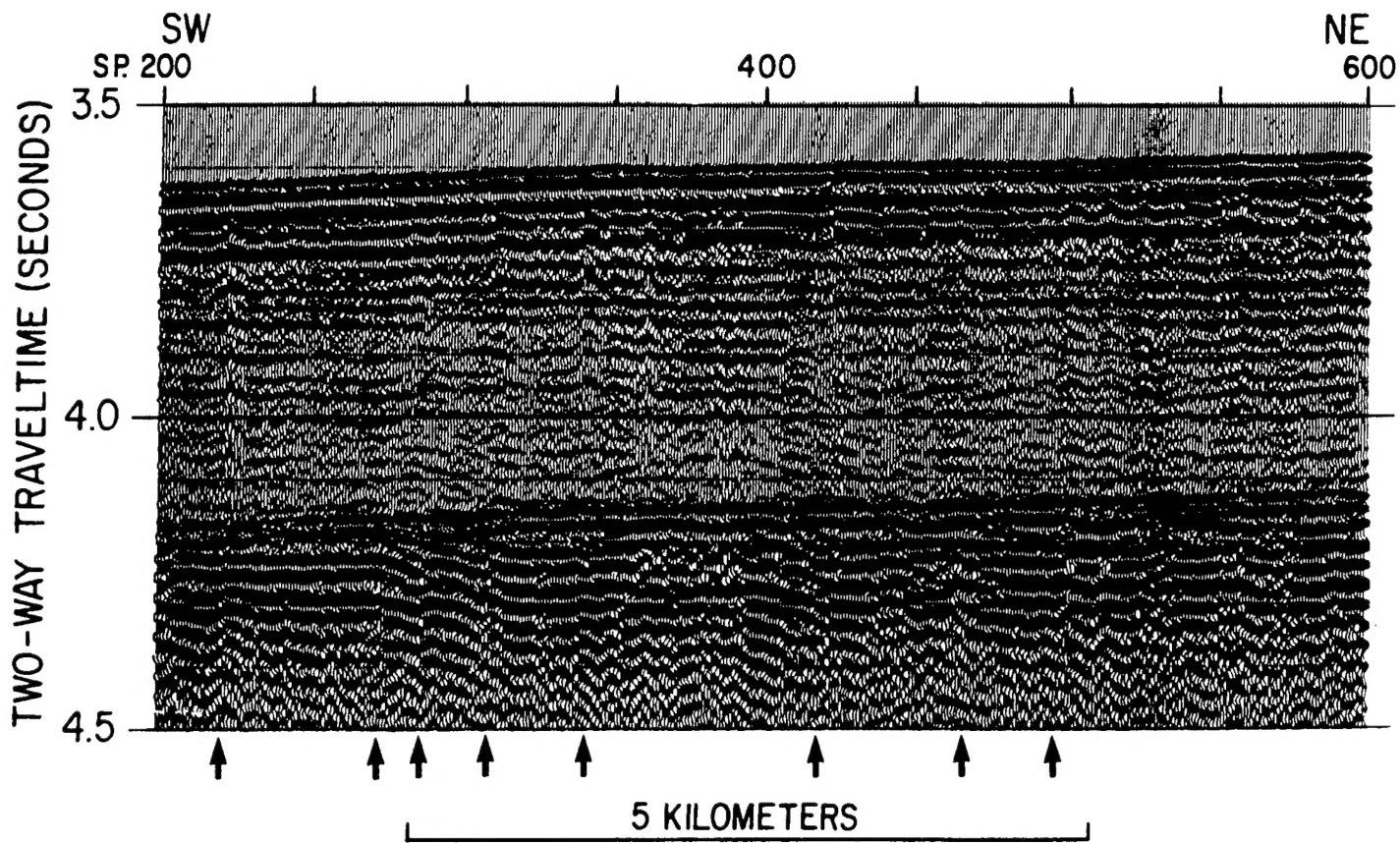


Fig.—8—Part of seismic line 11 showing apparent growth faults.